San Joaquin Renewables
Class VI Permit Application
AoR and Corrective Action Plan

Prepared for

San Joaquin Renewables LLC
McFarland, California

Submitted to

U.S. Environmental Protection Agency Region 9
San Francisco, California

Prepared by

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1.7 AoR Delineation

AoR delineation was based on the methods of Nicot et al. (2008), which is also referenced in the U.S. EPA AoR and Corrective Action Guidance. Specifically, the following equation was used (Eq-1):

$$\frac{\Delta P}{g} = (z_v - z_I)\left(\frac{\lambda - \xi}{2}(z_v - z_I) + \rho_{I,\lambda} - \rho_I\right)$$

where ΔP is the admissible overpressure that can be sustained before fluid in the injection zone would flow into a USDW through a hypothetical open conduit "threshold overpressure", g is acceleration due to gravity, z_v is the elevation of the injection zone, z_i is the lowermost elevation of the USDW, λ is a linear coefficient that describes the density gradient in the wellbore at a constant total dissolved solids (TDS), ξ is a linear coefficient that describes the initial density gradient in the borehole, $\rho_{I,\lambda}$ represents the density of fluid in the wellbore at the depth of the USDW after increased pressure has moved denser brine into the wellbore, and ρ_I is the initial density in the wellbore at the depth of the USDW. Equation 1 assumes that pressure increase is slow enough for the fluid to equilibrate thermally with its surroundings, and that additional pressure has to be balanced by the increase in density of the water column in the well bore.

Appendix B presents threshold overpressure calculations at example locations within the vicinity shown on Figure 1-22. Injection zone and USDW elevations are based on the digital model grid and USDW delineations presented in the narrative permit application report. TDS is based on salinity mapping also presented in the narrative permit application report. Linear coefficients are calculated based on density as a function of temperature and salinity using standard methods as given in Appendix B. Threshold pressure varies primarily based on the distance between the injection and the lowermost USDW, and ranges from 31,000 Pa at the intersection of cross-section D-D’ and A-A’ to 173,000 Pa at the CV Highway and Garces Highway. Threshold pressure is calculated to be 143,000 Pa at the injection well location.

The AoR was not delineated based on the manual calculations presented in Appendix B (given as informative examples); rather, the AoR was delineated by applying Equation 1 at each TOUGH model grid location based on the specific salinity, USDW elevation, and injection-zone formation elevations at each model grid cell location. The resulting AoR delineation is presented in Figure 1-22. As described above, overpressure increases during the injection phase of the project, and then generally decreases at the injection well location after injection ends. However, minor pressure increase is observed in areas distant from the injection well after injection ends. Threshold overpressure was evaluated at 15 years, 20 years, and 40 years (Figure 1-22). By 40 years (25 years after injection ends) threshold overpressure has dissipated to approximately zero. The final AoR delineation was based on the outermost threshold overpressure at 15 and 20 years.

Note that for the purpose of AoR delineation the easternmost model domain area, where Vedder formation salinity is less than 10,000 mg/L (generally to the east of cross-section D-D'; see the narrative permit application report) was assumed to have negligible overpressure. As noted above, simulated maximum overpressure in this area during the injection phase and afterwards is negligible (less than 0.2 bars). Furthermore, freshwater recharge along the Sierra Nevada mountain foothills and tributaries such as Poso Creek result in a downwards hydraulic gradient violating the conservative hydrostatic assumptions used herein (GEI, 2020). Similarly, previous oil and gas extraction in this area should also result in lower initial pressures in the deeper geologic formations.

Figure 1-23 presents an overlay of the final delineated AoR and the maximum extent of supercritical-phase carbon dioxide (115 years after the simulation begins, or 100 years after injection ends). The AoR must encompass the maximum extent of the threshold overpressure and supercritical carbon dioxide. Figure 1-23 confirms that the AoR encompasses the full extent of supercritical carbon dioxide.

1.8 AoR Reevaluation

Consistent with U.S. EPA regulations and guidance, the AoR will be reevaluated at a fixed frequency of once every five years and under additional conditions as described below:

- After injection well construction and pre-injection testing and logging, to incorporate additional geologic information obtained from core analyses and additional injection well tests
- Significant changes in site operations that may alter model predictions and the AoR delineation
- Monitoring results for the injected carbon dioxide plume and/or the associated pressure front that differ significantly from model predictions

References

Doughty, C. A., 2013. User's guide for hysteretic capillary pressure and relative permeability functions in TOUGH2. No. LBNL-6533E. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2013.

Doughty, C., 2010. Investigation of CO2 plume behavior for a large-scale pilot test of geologic carbon storage in a saline formation, Transp. Porous Med., 82, 49–76, 2010.

Finsterle, S., 2021. iTOUGH2-EOS1nT: A Nonisothermal Two-Phase Flow Simulator for Water and Multiple Tracers User’s Guide. Finsterle GeoConsulting, Kensington CA, July, 19 2021.

Finsterle, S., Commer, M., Edmiston, J. K., Jung, Y., Kowalsky, M. B., Pau, G. S. H., ... & Zhang, Y. (2017). iTOUGH2: A multiphysics simulation-optimization framework for analyzing subsurface systems. Computers & Geosciences, 108, 8-20.

Nicot, J.-P., Oldenburg, C.M., Bryant, S.L., Hovorka, S.D., 2008. Pressure perturbations from geologic carbon sequestration: Area-of-review boundaries and borehole leakage driving forces: presented at the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9), Washington, D.C., November 16-20, 2008. GCCC Digital Publication Series #08-03h.

Pruess, K., C. Oldenburg, and G. Moridis, 2012. TOUGH2 User’s Guide, Version 2.1, Report LBNL-43134, Lawrence Berkeley National Laboratory, Berkeley, Calif., 2012.

Pruess, K. (2005). ECO2N: A TOUGH2 fluid property module for mixtures of water, NaCl, and CO2 (p. 76). Berkeley, CA: Lawrence Berkeley National Laboratory.

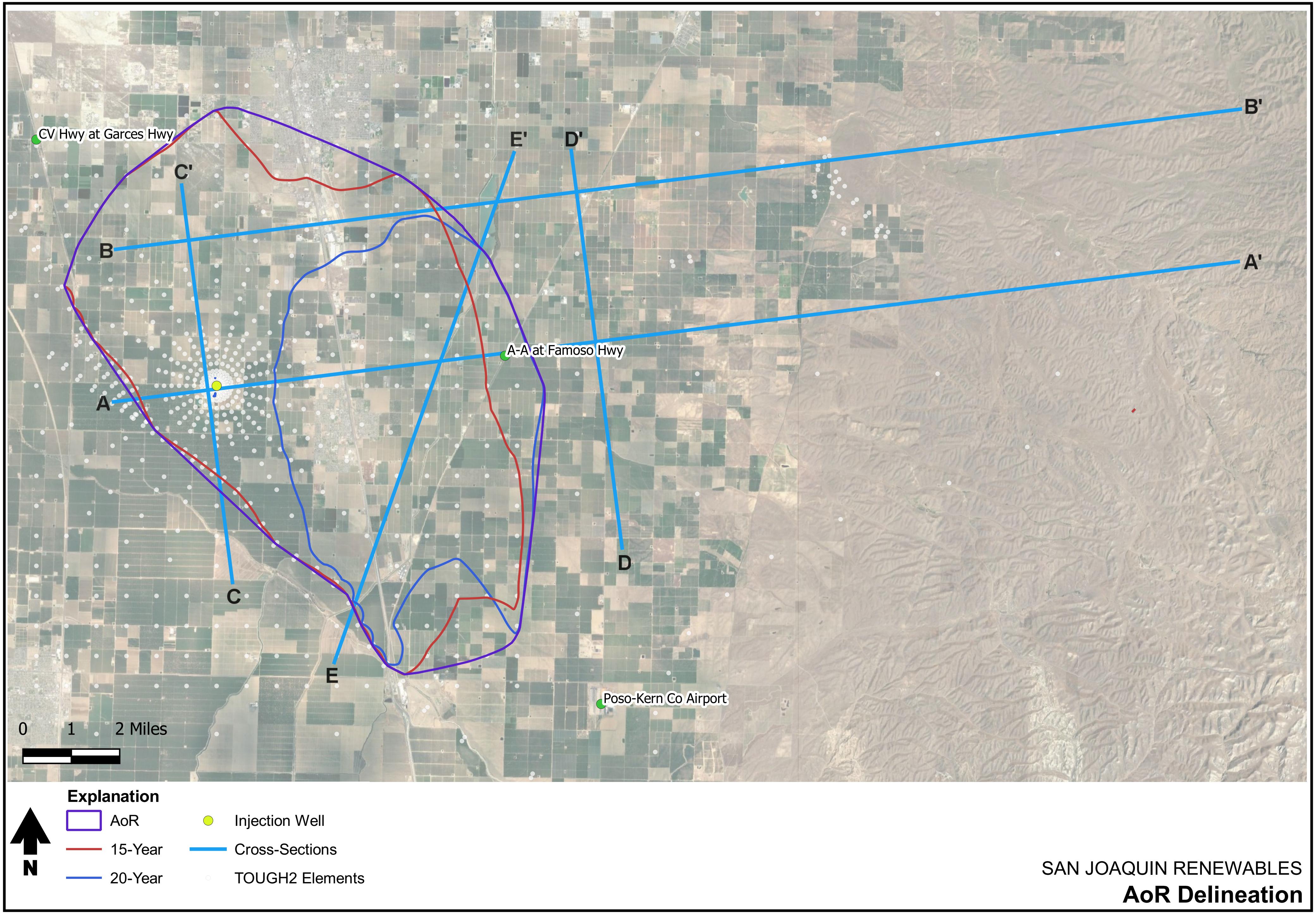
Pruess, K., J. Garcia, T. Kovscek, C. Oldenburg, J. Rutqvist, C. Steefel, and T. Xu. 2004. Code intercomparison builds confidence in numerical simulation models for geologic disposal of CO2. Energy 29:1431–1444.

Rinaldi, A.P., V. Vilarrasa, J. Rutqvist and F. Cappa. 2015. Fault reactivation during CO2 sequestration: Effects of well orientation on seismicity and leakage. Greenhouse Gas Sci Technol. 5:645–656 (2015); DOI: 10.1002/ghg

Spycher, N., Pruess, K., & Ennis-King, J. (2003). CO2-H2O mixtures in the geological sequestration of CO2. I. Assessment and calculation of mutual solubilities from 12 to 100 C and up to 600 bar. Geochimica et cosmochimica acta, 67(16), 3015-3031.

Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil science society of America journal, 44(5), 892-898.

Figures

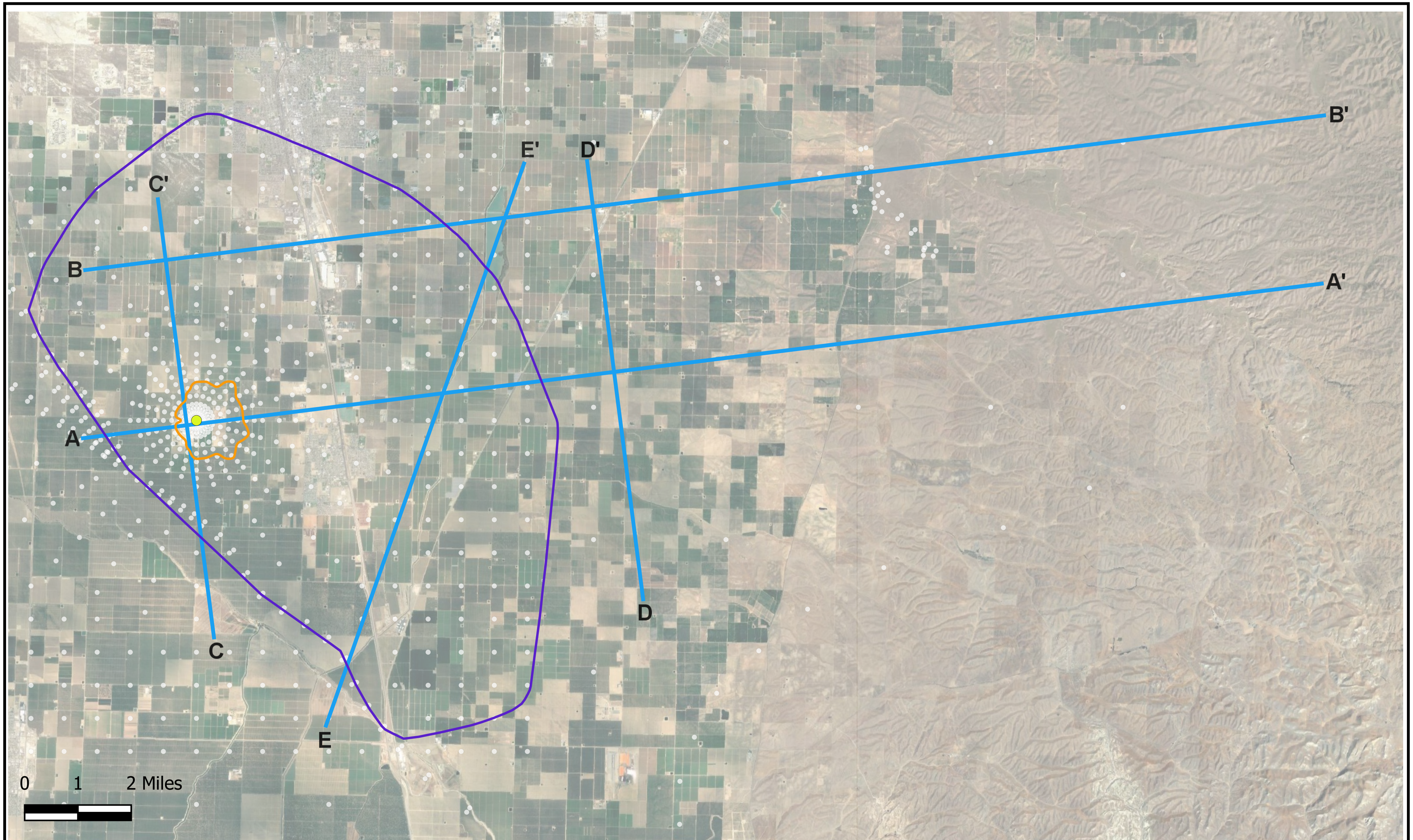


SAN JOAQUIN RENEWABLES

AoR Delineation

10/13/2021 JN DB19.1252

Figure 1-22



Explanation

AoR
115-Year
Injection Well
Cross-Sections
TOUGH2 Elements

N

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SAN JOAQUIN RENEWABLES

AoR Delineation and Maximum Extent of Carbon Dioxide Saturation

07/14/2021 JN DB19.1252

Figure 1-23

Appendix B: AoR Delineation Calculations

Location	At injection Well
X	294000
Y	3951600

Symbol	Parameter	Value	Units
z_i	Depth, injection zone	2351	m
z_u	Depth, USDW	740	m
TDS,i	TDS, injection zone	25000	mg/L
TDS,u	TDS, USDW	500	mg/L
T	Average surface temperature	18.9	C
ΔT	Geothermal Gradient	25	C/km
g	Gravitational constant	9.81	m/s^2
λ	Density gradient at constant TDS	-1.22E-05	kg/L*m
		-1.22E-02	kg/m^3*m
ξ	Initial density gradient in borehole	-1.03E-06	kg/L*m
		-1.03E-03	kg/m^3*m
Δρ	Final density difference at USDW base	0.018	kg/L
		18.05	kg/m^3
ΔP	**Maximum admissible pressure**	**142622**	**Pa**

	Depth (m)	T, °C	A	B	Rho (kg/m^3)	ρ, TDS = 500 mg/L (kg/L)	ρ, TDS = 25,000 mg/L (kg/L)
	500	31.4	0.75	-0.004	995.247	0.996	1.014
	750	37.7	0.75	-0.004	993.125	0.993	1.012
	1000	43.9	0.74	-0.004	990.700	0.991	1.009
	1250	50.2	0.74	-0.005	987.995	0.988	1.006
	1500	56.4	0.74	-0.005	985.030	0.985	1.003
	1750	62.7	0.75	-0.006	981.821	0.982	1.000
	2000	68.9	0.76	-0.007	978.378	0.979	0.997
	2250	75.2	0.77	-0.007	974.714	0.975	0.993
	2500	81.4	0.79	-0.008	970.836	0.971	0.990
	2750	87.7	0.81	-0.009	966.751	0.967	0.986
USDW	740	37.4	0.75	-0.004	993.216	0.994	1.012
Injection	2351	77.7	0.78	-0.008	973.172	0.974	0.992

Earthward Consulting, 2016

Water density as function of temperature and concentration

McCutcheon, S.C., Martin, J.L, Barnwell, T.O. Jr. 1993. Water Quality in Maidment, D.R. (Editor). Handbood of Hydrology, McGraw-Hill, New York, NY (p. 11.3)

Water density as a function of temperature only

rho = density in kg/m^3 as a function of temperature

T = temperature in C

rho = 1000(1 - (T+288.9414)/(508929.2*(T+68.12963))*(T-3.9863)^2)

Water density as a function of temperature and salinity

rhos = density in kg/m^3 as a function of temperature and salinity

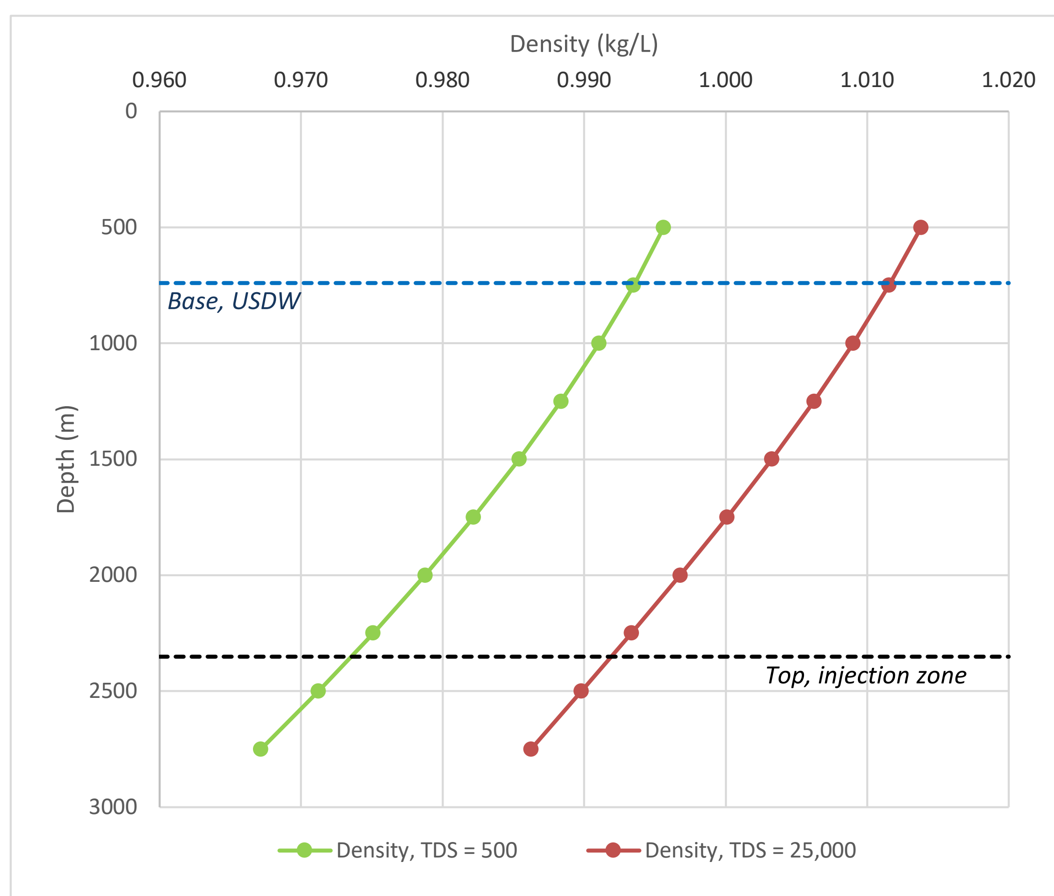
S = salinity in g/kg

rhos = rho + AS + BS^(3/2) + CS^2

A = 8.24493E-1 - 4.0899E-3*T + 7.6438E-5*T^2 -8.2467E-7*T^3 + 5.3675E-9*T^4

B = -5.724E-3 + 1.0227E-4*T - 1.6546E-6*T^2

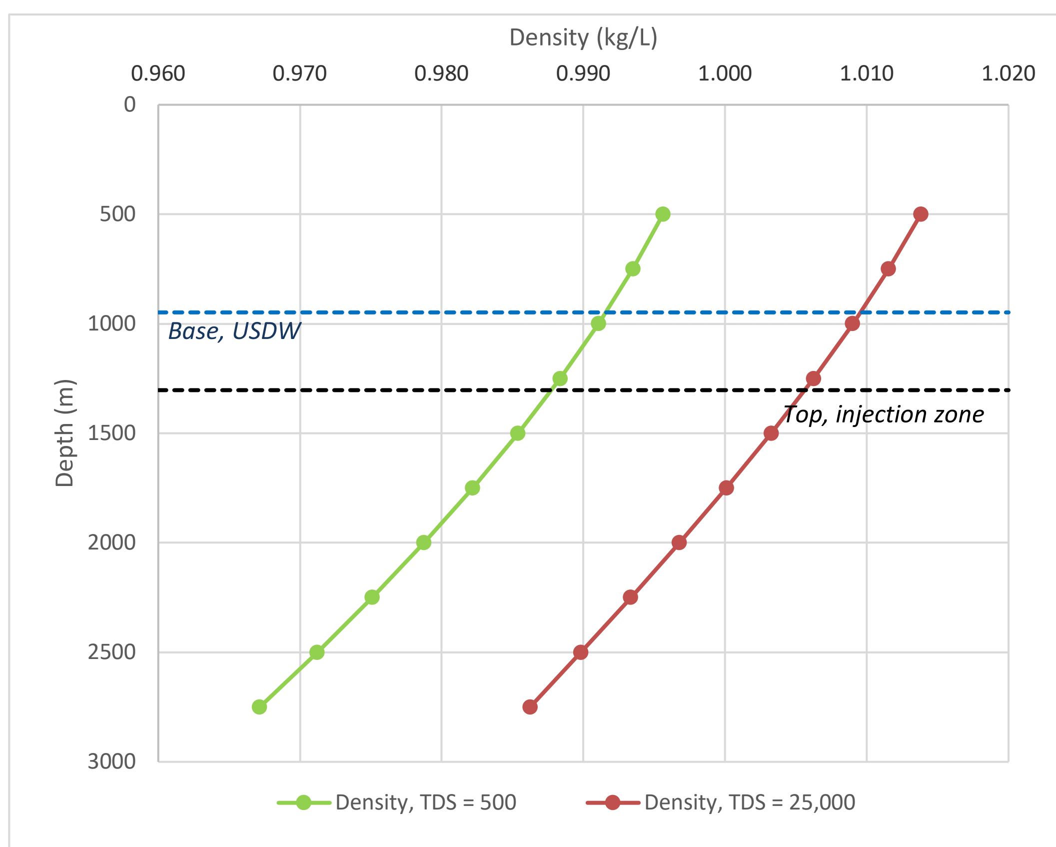
C = 4.8314E-4



Location	D-D' at A-A'
X	306600
Y	3953000

Symbol	Parameter	Value	Units
z_i	Depth, injection zone	1303	m
z_u	Depth, USDW	948	m
TDS,i	TDS, injection zone	25000	mg/L
TDS,u	TDS, USDW	500	mg/L
T	Average surface temperature	18.9	C
ΔT	Geothermal Gradient	25	C/km
g	Gravitational constant	9.81	m/s^2
λ	Density gradient at constant TDS	-1.11E-05	kg/L*m
		-1.11E-02	kg/m^3*m
ξ	Initial density gradient in borehole	3.95E-05	kg/L*m
		3.95E-02	kg/m^3*m
Δρ	Final density difference at USDW base	0.018	kg/L
		17.96	kg/m^3
ΔP	**Maximum admissible pressure**	**31270**	**Pa**

	Depth (m)	T, °C	A	B	Rho (kg/m^3)	ρ, TDS = 500 mg/L (kg/L)	ρ, TDS = 25,000 mg/L (kg/L)
	500	31.4	0.75	-0.004	995.247	0.996	1.014
	750	37.7	0.75	-0.004	993.125	0.993	1.012
	1000	43.9	0.74	-0.004	990.700	0.991	1.009
	1250	50.2	0.74	-0.005	987.995	0.988	1.006
	1500	56.4	0.74	-0.005	985.030	0.985	1.003
	1750	62.7	0.75	-0.006	981.821	0.982	1.000
	2000	68.9	0.76	-0.007	978.378	0.979	0.997
	2250	75.2	0.77	-0.007	974.714	0.975	0.993
	2500	81.4	0.79	-0.008	970.836	0.971	0.990
	2750	87.7	0.81	-0.009	966.751	0.967	0.986
USDW	948	42.6	0.74	-0.004	991.228	0.992	1.010
Injection	1303	51.5	0.74	-0.005	987.388	0.988	1.006



Earthward Consulting, 2016

Water density as function of temperature and concentration

McCutcheon, S.C., Martin, J.L, Barnwell, T.O. Jr. 1993. Water Quality in Maidment, D.R. (Editor). Handbood of Hydrology, McGraw-Hill, New York, NY (p. 11.3)

Water density as a function of temperature only

rho = density in kg/m^3 as a function of temperature

T = temperature in C

rho = 1000(1 - (T+288.9414)/(508929.2*(T+68.12963))*(T-3.9863)^2)

Water density as a function of temperature and salinity

rhos = density in kg/m^3 as a function of temperature and salinity

S = salinity in g/kg

rhos = rho + AS + BS^(3/2) + CS^2

A = 8.24493E-1 - 4.0899E-3*T + 7.6438E-5*T^2 -8.2467E-7*T^3 + 5.3675E-9*T^4

B = -5.724E-3 + 1.0227E-4*T - 1.6546E-6*T^2

C = 4.8314E-4

Location	E-E at B-B
X	303400
Y	3957800

Symbol	Parameter	Value	Units
z_i	Depth, injection zone	1472	m
z_u	Depth, USDW	798	m
TDS,i	TDS, injection zone	25000	mg/L
TDS,u	TDS, USDW	500	mg/L
T	Average surface temperature	18.9	C
ΔT	Geothermal Gradient	25	C/km
g	Gravitational constant	9.81	m/s^2
λ	Density gradient at constant TDS	-1.11E-05	kg/L*m
		-1.11E-02	kg/m^3*m
ξ	Initial density gradient in borehole	1.57E-05	kg/L*m
		1.57E-02	kg/m^3*m
Δρ	Final density difference at USDW base	0.018	kg/L
		18.02	kg/m^3
ΔP	**Maximum admissible pressure**	**59577**	**Pa**

	Depth (m)	T, °C	A	B	Rho (kg/m^3)	ρ, TDS = 500 mg/L (kg/L)	ρ, TDS = 25,000 mg/L (kg/L)
	500	31.4	0.75	-0.004	995.247	0.996	1.014
	750	37.7	0.75	-0.004	993.125	0.993	1.012
	1000	43.9	0.74	-0.004	990.700	0.991	1.009
	1250	50.2	0.74	-0.005	987.995	0.988	1.006
	1500	56.4	0.74	-0.005	985.030	0.985	1.003
	1750	62.7	0.75	-0.006	981.821	0.982	1.000
	2000	68.9	0.76	-0.007	978.378	0.979	0.997
	2250	75.2	0.77	-0.007	974.714	0.975	0.993
	2500	81.4	0.79	-0.008	970.836	0.971	0.990
	2750	87.7	0.81	-0.009	966.751	0.967	0.986
USDW	798	38.9	0.74	-0.004	992.682	0.993	1.011
Injection	1472	55.7	0.74	-0.005	985.375	0.986	1.004

Earthward Consulting, 2016

Water density as function of temperature and concentration

McCutcheon, S.C., Martin, J.L, Barnwell, T.O. Jr. 1993. Water Quality in Maidment, D.R. (Editor). Handbood of Hydrology, McGraw-Hill, New York, NY (p. 11.3)

Water density as a function of temperature only

rho = density in kg/m^3 as a function of temperature

T = temperature in C

rho = 1000(1 - (T+288.9414)/(508929.2*(T+68.12963))*(T-3.9863)^2)

Water density as a function of temperature and salinity

rhos = density in kg/m^3 as a function of temperature and salinity

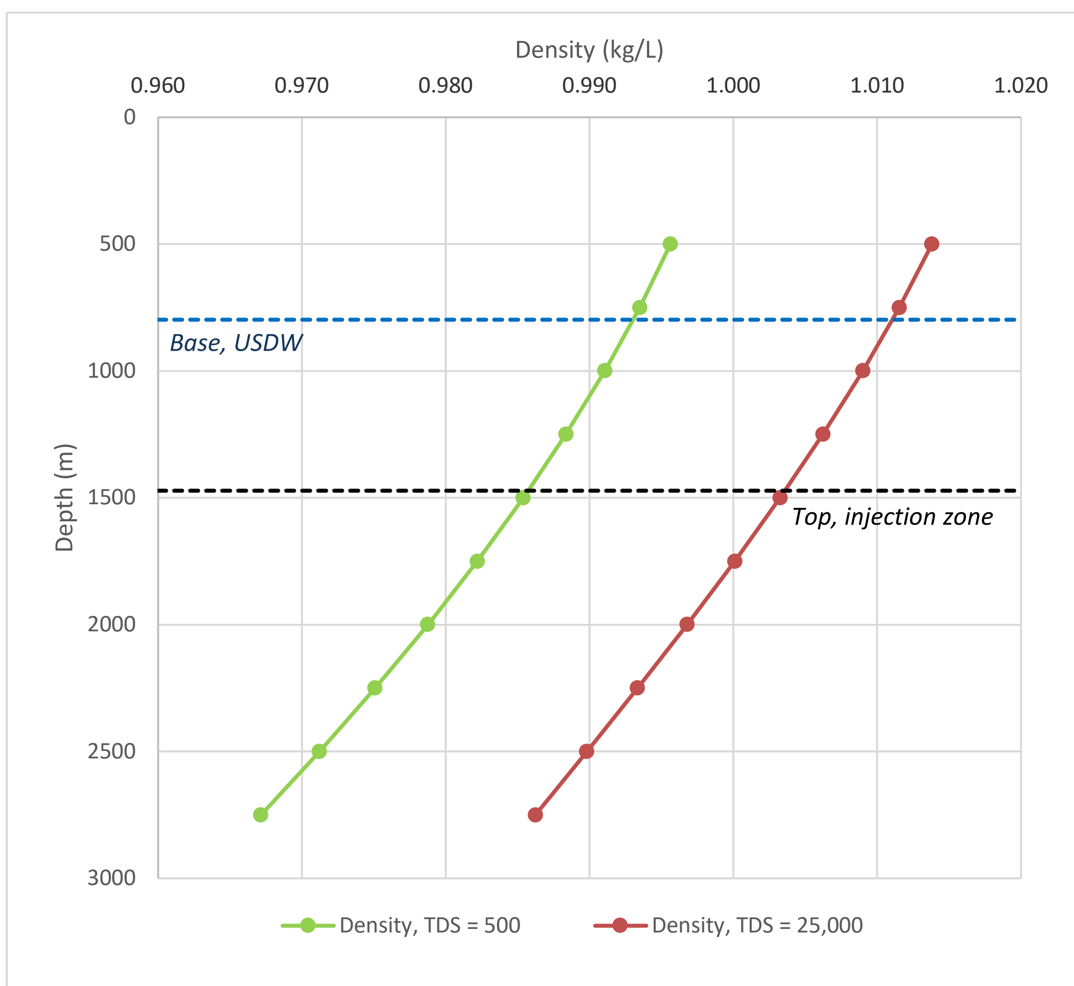
S = salinity in g/kg

rhos = rho + AS + BS^(3/2) + CS^2

A = 8.24493E-1 - 4.0899E-3*T + 7.6438E-5*T^2 -8.2467E-7*T^3 + 5.3675E-9*T^4

B = -5.724E-3 + 1.0227E-4*T - 1.6546E-6*T^2

C = 4.8314E-4



Location	A-A' at Famoso Hwy
X	303600
Y	3952600

Symbol	Parameter	Value	Units
z_i	Depth, injection zone	1526	m
z_u	Depth, USDW	850	m
TDS,i	TDS, injection zone	25000	mg/L
TDS,u	TDS, USDW	500	mg/L
T	Average surface temperature	18.9	C
ΔT	Geothermal Gradient	25	C/km
g	Gravitational constant	9.81	m/s^2
λ	Density gradient at constant TDS	-1.13E-05	kg/L*m
		-1.13E-02	kg/m^3*m
ξ	Initial density gradient in borehole	1.54E-05	kg/L*m
		1.54E-02	kg/m^3*m
Δρ	Final density difference at USDW base	0.018	kg/L
		18.00	kg/m^3
ΔP	**Maximum admissible pressure**	**59676**	**Pa**

	Depth (m)	T, °C	A	B	Rho (kg/m^3)	ρ, TDS = 500 mg/L (kg/L)	ρ, TDS = 25,000 mg/L (kg/L)
	500	31.4	0.75	-0.004	995.247	0.996	1.014
	750	37.7	0.75	-0.004	993.125	0.993	1.012
	1000	43.9	0.74	-0.004	990.700	0.991	1.009
	1250	50.2	0.74	-0.005	987.995	0.988	1.006
	1500	56.4	0.74	-0.005	985.030	0.985	1.003
	1750	62.7	0.75	-0.006	981.821	0.982	1.000
	2000	68.9	0.76	-0.007	978.378	0.979	0.997
	2250	75.2	0.77	-0.007	974.714	0.975	0.993
	2500	81.4	0.79	-0.008	970.836	0.971	0.990
	2750	87.7	0.81	-0.009	966.751	0.967	0.986
USDW	850	40.2	0.74	-0.004	992.190	0.993	1.011
Injection	1526	57.1	0.74	-0.005	984.708	0.985	1.003

Earthward Consulting, 2016

Water density as function of temperature and concentration

McCutcheon, S.C., Martin, J.L, Barnwell, T.O. Jr. 1993. Water Quality in Maidment, D.R. (Editor). Handbood of Hydrology, McGraw-Hill, New York, NY (p. 11.3)

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S = salinity in g/kg

rhos = rho + AS + BS^(3/2) + CS^2

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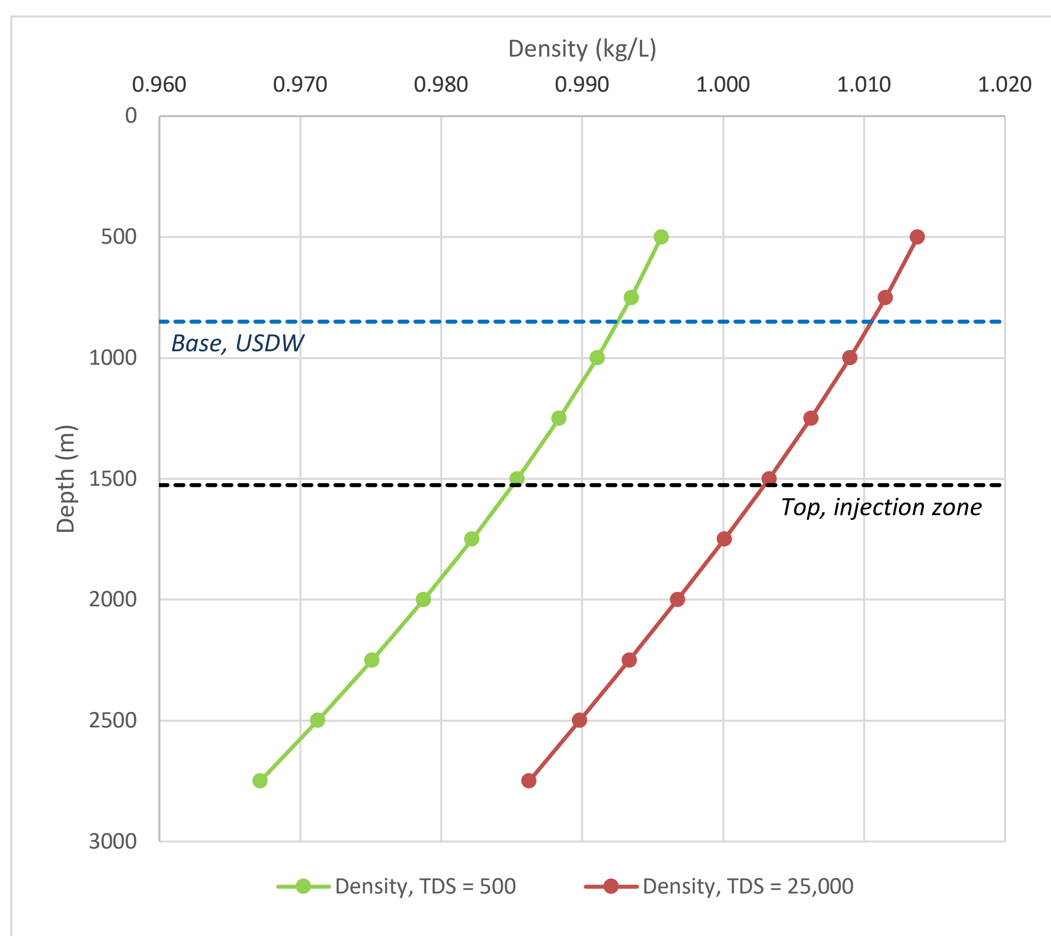
B = -5.724E-3 + 1.0227E-4*T - 1.6546E-6*T^2

C = 4.8314E-4



Location	Poso Kern Co Airport
X	306800
Y	3941000

Symbol	Parameter	Value	Units
z_i	Depth, injection zone	1577	m
z_u	Depth, USDW	876	m
TDS,i	TDS, injection zone	25000	mg/L
TDS,u	TDS, USDW	500	mg/L
T	Average surface temperature	18.9	C
ΔT	Geothermal Gradient	25	C/km
g	Gravitational constant	9.81	m/s^2
λ	Density gradient at constant TDS	-1.14E-05	kg/L*m
		-1.14E-02	kg/m^3*m
ξ	Initial density gradient in borehole	1.43E-05	kg/L*m
		1.43E-02	kg/m^3*m
Δρ	Final density difference at USDW base	0.018	kg/L
		17.99	kg/m^3
ΔP	**Maximum admissible pressure**	**61845**	**Pa**

	Depth (m)	T, °C	A	B	Rho (kg/m^3)	ρ, TDS = 500 mg/L (kg/L)	ρ, TDS = 25,000 mg/L (kg/L)
	500	31.4	0.75	-0.004	995.247	0.996	1.014
	750	37.7	0.75	-0.004	993.125	0.993	1.012
	1000	43.9	0.74	-0.004	990.700	0.991	1.009
	1250	50.2	0.74	-0.005	987.995	0.988	1.006
	1500	56.4	0.74	-0.005	985.030	0.985	1.003
	1750	62.7	0.75	-0.006	981.821	0.982	1.000
	2000	68.9	0.76	-0.007	978.378	0.979	0.997
	2250	75.2	0.77	-0.007	974.714	0.975	0.993
	2500	81.4	0.79	-0.008	970.836	0.971	0.990
	2750	87.7	0.81	-0.009	966.751	0.967	0.986
USDW	876	40.8	0.74	-0.004	991.939	0.992	1.010
Injection	1577	58.3	0.74	-0.005	984.067	0.984	1.002

Earthward Consulting, 2016

Water density as function of temperature and concentration

McCutcheon, S.C., Martin, J.L, Barnwell, T.O. Jr. 1993. Water Quality in Maidment, D.R. (Editor). Handbood of Hydrology, McGraw-Hill, New York, NY (p. 11.3)

Water density as a function of temperature only

rho = density in kg/m^3 as a function of temperature

T = temperature in C

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Water density as a function of temperature and salinity

rhos = density in kg/m^3 as a function of temperature and salinity

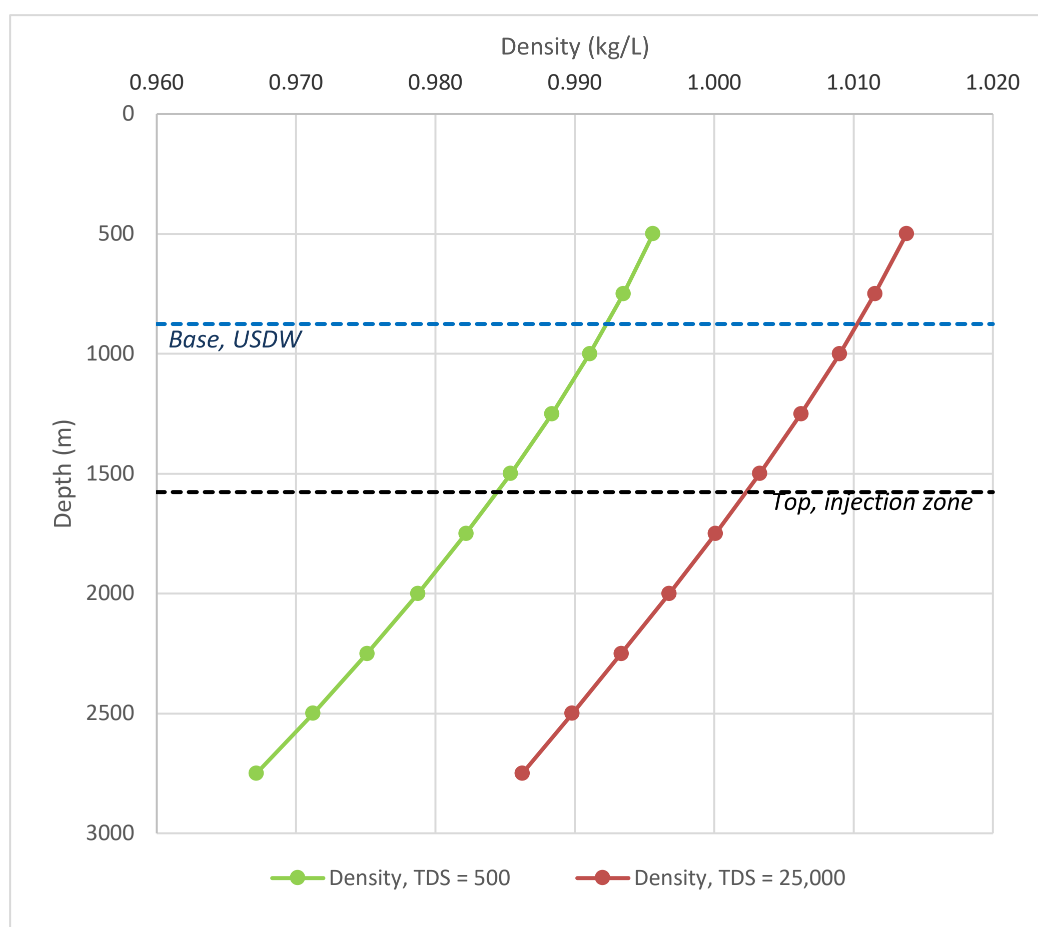
S = salinity in g/kg

rhos = rho + AS + BS^(3/2) + CS^2

A = 8.24493E-1 - 4.0899E-3*T + 7.6438E-5*T^2 -8.2467E-7*T^3 + 5.3675E-9*T^4

B = -5.724E-3 + 1.0227E-4*T - 1.6546E-6*T^2

C = 4.8314E-4



Location	CV Hwy at Garces Hwy
X	288000
Y	3959800

Symbol	Parameter	Value	Units
z_i	Depth, injection zone	2574	m
z_u	Depth, USDW	626	m
TDS,i	TDS, injection zone	25000	mg/L
TDS,u	TDS, USDW	500	mg/L
T	Average surface temperature	18.9	C
ΔT	Geothermal Gradient	25	C/km
g	Gravitational constant	9.81	m/s^2
λ	Density gradient at constant TDS	-1.23E-05	kg/L*m
		-1.23E-02	kg/m^3*m
ξ	Initial density gradient in borehole	-2.99E-06	kg/L*m
		-2.99E-03	kg/m^3*m
Δρ	Final density difference at USDW base	0.018	kg/L
		18.11	kg/m^3
ΔP	**Maximum admissible pressure**	**173043**	**Pa**

	Depth (m)	T, °C	A	B	Rho (kg/m^3)	ρ, TDS = 500 mg/L (kg/L)	ρ, TDS = 25,000 mg/L (kg/L)
	500	31.4	0.75	-0.004	995.247	0.996	1.014
	750	37.7	0.75	-0.004	993.125	0.993	1.012
	1000	43.9	0.74	-0.004	990.700	0.991	1.009
	1250	50.2	0.74	-0.005	987.995	0.988	1.006
	1500	56.4	0.74	-0.005	985.030	0.985	1.003
	1750	62.7	0.75	-0.006	981.821	0.982	1.000
	2000	68.9	0.76	-0.007	978.378	0.979	0.997
	2250	75.2	0.77	-0.007	974.714	0.975	0.993
	2500	81.4	0.79	-0.008	970.836	0.971	0.990
	2750	87.7	0.81	-0.009	966.751	0.967	0.986
USDW	626	34.6	0.75	-0.004	994.217	0.995	1.013
Injection	2574	83.3	0.80	-0.009	969.648	0.970	0.989

<u>Earthward Consulting, 2016</u>

Water density as function of temperature and concentration

McCutcheon, S.C., Martin, J.L, Barnwell, T.O. Jr. 1993. Water Quality in Maidment, D.R. (Editor). Handbood of Hydrology, McGraw-Hill, New York, NY (p. 11.3)

Water density as a function of temperature only

rho = density in kg/m^3 as a function of temperature

T = temperature in C

rho = 1000(1 - (T+288.9414)/(508929.2*(T+68.12963))*(T-3.9863)^2)

Water density as a function of temperature and salinity

rhos = density in kg/m^3 as a function of temperature and salinity

S = salinity in g/kg

rhos = rho + AS + BS^(3/2) + CS^2

A = 8.24493E-1 - 4.0899E-3*T + 7.6438E-5*T^2 -8.2467E-7*T^3 + 5.3675E-9*T^4

B = -5.724E-3 + 1.0227E-4*T - 1.6546E-6*T^2

C = 4.8314E-4